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# LABORATORY SIMULATION OF THE ROCKET MOTOR THRUST AS A "FOLLOWER" FORCE

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Ground tests of solid propellant rocket motors have shown that metal-containing propellants produce various amounts of slag (primarily aluminum oxide), which is trapped in the motor case causing a loss of specific impulse. Although not yet definitely established, the presence of a liquid pool of slag also may contribute to nutational instabilities that have been observed with certain spin-stabilized, upper-stage vehicles. Because of the rocket's axial acceleration—absent in the ground tests—estimates of in-flight slag mass have been very uncertain. Yet such estimates are needed to determine the magnitude of the control authority of the systems required for eliminating the instability. A test rig with an eccentrically mounted hemispherical bowl was designed and built that incorporates a "follower" force that properly aligns the thrust vector along the axis of spin. A program that computes the motion of a point mass in the spinning and precessing bowl was written. Using various rpm, friction factors, and initial starting conditions, plots were generated showing the trace of the point mass around the inside of the fuel tank. The apparatus will be used extensively during the 1990-1991 academic year and incorporate future design features such as a variable nutation angle and a film height measuring instrument. Data obtained on the nutational instability characteristics will be used to determine order-of-magnitude estimates of control authority needed to minimize the sloshing effect.

## INTRODUCTION

Many rocket motor solid propellants in current use contain a significant amount of aluminum, which, when burned, produces a slag consisting of aluminum oxide and elemental aluminum. Most of this material is expelled through the rocket motor nozzle and adds to the thrust, but some remains trapped in the motor case. The melting point of the $\alpha$-form of $Al_2O_3$ is about 2050°C, below the temperature of the combustion gas. The liquid slag, in the form of small droplets, is subject to a combination of forces that include the drag from the combustion gas, the inertial force resulting from the axial acceleration of the rocket, and (for spin-stabilized vehicles) the centrifugal force resulting from the vehicle spin.

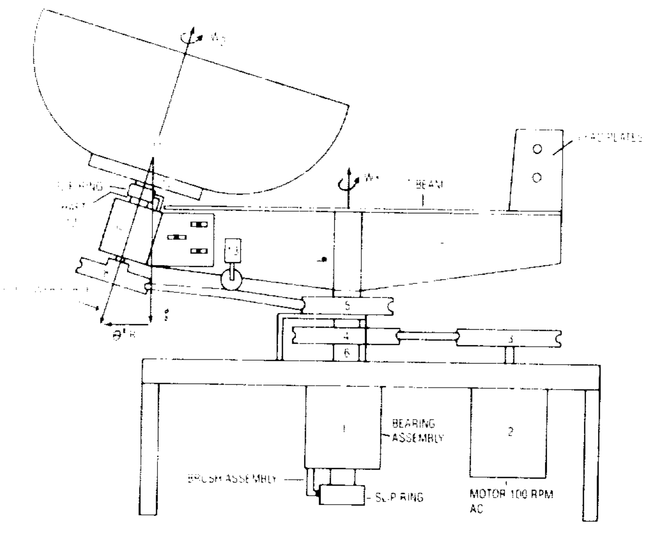
The present analysis postulates that, because of the high level of turbulence in the motor, slag droplets entering the gas stream are ejected, and that trapped slag is formed primarily by liquid slag flowing along the surfaces toward the point of minimum potential energy in the accelerating and spinning motor. Also, the present analysis concludes that slag will accumulate to some degree in all spinning or accelerating rocket motors with aluminum-containing propellants and submerged nozzles.

A number of spin-stabilized vehicles that use aluminized propellant have shown a marked tendency for a "coning" instability, i.e., a precession with steadily increasing nutation angle. These motors have a submerged nozzle geometry, resulting in a downstream annular pocket that is likely to favor slag retention. It has been surmised, therefore, that the sloshing motion of a liquid slag pool may be a contributing cause of the observed flight instability. The effects of liquid slag on the stability of spinning vehicles is similar to the effects produced by fuel slosh in spacecraft. Slag retention also requires examination because of its potentially deleterious effect on specific impulse.

Through installation of witness plates downstream of the nozzle, where some of the (now solid) slag particles are deposited, estimates of the size distribution and total mass of the expelled particles have been made. Ground tests of this type, however, take no account of the precessing of the droplets in the nozzle.

This report consists of a mechanical design that simulates the motion of a spherical fuel tank in a thrusting spacecraft. A true simulation of the thrust was thought to be impossible because of the gravitational forces present in the laboratory. However, through the means of an eccentrically mounted spacecraft model on the top of a turntable, the simulation of thrust aligned with the vehicle axis is possible. The mechanical design was finished during the 1990 winter quarter and the test rig was built in the spring. Comparison of the initial description (see Fig. 1) with the design actually built (see Fig. 2) shows the evolution of the design concept. Qualitative analysis will be provided by photographs of fluid profiles at given time intervals and quantitative analysis by correlation of film thickness from capacitance measurements between two platinum wires located in the bowl. This sensor will be designed, built, and incorporated into the test rig slip-ring assembly during the 1990-1991 academic year. From these data, nutational instability characteristics and order-of-magnitude estimates of control authority needed to eliminate the instability will be determined.

A computer program was written to simulate the shape of a fluid in a spinning and precessing container with a nutation angle equal to zero. The fluid was assumed to be in hydrostatic equilibrium. The fluid depth as a function of position along with the shoreline of the fluid was determined. A more general code was written that computes the motion of a point mass in a spinning and precessing hemispherical container. Using




1. general bearing assembly
2. AC motor (variable rpm)
3. pulley for motor shaft
4. main drive pulley
5. secondary pulley (stationary)
6. main shaft
7. control arm
8. bowl pulley
9. bowl bearing housing assembly
10. bowl mounting flange
11. hemispherical bowl (lucite)
12. bowl suport shaft
13. idler guide

Fig. 1. Apparatus Diagram (Not to scale)

various rpm and friction factors, plots were generated to compare the motion of the point mass and validate the theoretical model (see Fig. 3).

## VISCOUS DISSIPATION

The degree of instability of a thrusting, spin-stabilized spacecraft depends strongly on the amount of internal energy dissipation. The dominant energy dissipation mechanism is thought to be the sloshing of liquid slag at the bottom of the solid motor casing, which directly influences the body's motion. Oscillatory, and sometimes violent, motion of the fluid induces corresponding oscillations in the body. Viscous effects in the fluid also influence the body causing the nutation angle to change, thereby affecting stability. It is, therefore, important to estimate the energy losses in the fluid.

Once these energy losses are estimated, one can predict the body motion by reducing its kinetic energy at the same rate. This approach is known as the "energy sink" procedure. Due to the growing nutation angle from energy dissipation, thrust corrections need to be made to stabilize the craft. This requires more fuel to be included for stabilization during launch, which ultimately increases launch mass. Having to fire these correcting thrusters at the right time creates yet another problem in the attitude dynamics and control of the spacecraft. Ideally, nutational instability characteristics and order-of-magnitude estimates of control authority needed to eliminate the instability would allow designers to provide the lightest control system necessary to minimize this phenomenon.

(a)

(b)

Fig. 2. Completed Test Rig: (a) Top View Showing Liquid Sloshing in Bowl; (b) Side View Showing Dual Motor Assembly

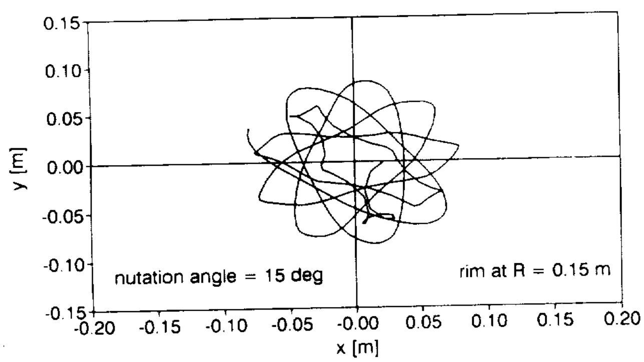



Fig. 3. Follow Force Diagram

## SCALE-MODEL PRINCIPLES

Many different models have been developed to test sloshing and its effect on spacecraft. Most of these models, however, are made to simulate the sloshing of a spacecraft in which thrust is absent. One of the recent problems is that an instability evidenced by a growing nutation angle has been observed during the firing of liquid and solid perigee and apogee motors. A new model to simulate this motion was needed that properly aligns the "thrust" vector with the model axis.

A simple design of a spacecraft model mounted eccentrically on a turntable can be used. This rig simulates the thrust as a "follower" force (see Fig. 4). Previous models were subjected to gravity forces acting at the center of mass, but the new model produces a combination of gravity and inertial forces that remains aligned at all times with the vehicle axis. Hence, this thrust "follows" the model as it spins and precesses on the turntable.

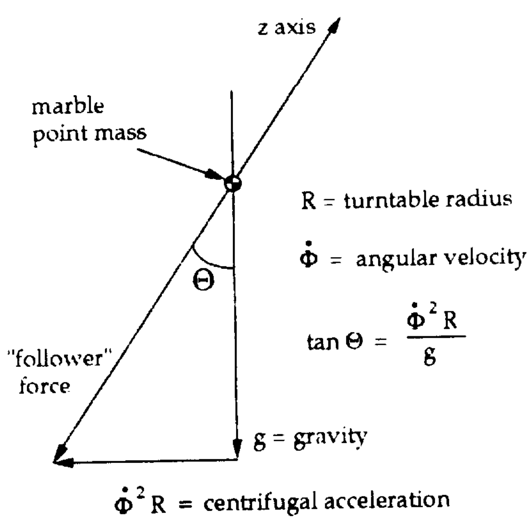



Fig. 4. Computer Code Results: Ten Second Marble Trace

Because of space and cost constraints, it is necessary to have a model that is not full scale. It must then be shown that the model behaves in the same way as the spacecraft. Therefore, it is required for the model to have the same inertia ratio as the spacecraft

$$\left[\frac{Is}{Ip}\right]_{model} = \left[\frac{Is}{Ip}\right]_{spacecraft}$$

It also follows that the ratio of the precession rate to the spin rate be the same in both the model and the full-scale spacecraft. To simulate the dynamics of the sloshing requires that the Froude numbers of the model and spacecraft be the same

$$\text{Froude number} \equiv \left[\frac{Rt(d\Phi dt)^2}{g/\cos\theta}\right]_{model} = \left[\frac{Rt(d\Phi dt)^2}{T/M}\right]_{spacecraft}$$

Solving for $(d\Phi/dt)_{model}$

$$(d\Phi/dt)_{model} = (d\Phi/dt)_{spacecraft}\sqrt{\frac{(Rt)_{spacecraft}\, g\, M}{(Rt)_{model}\, T\cos\theta o}}$$

Using these equations, a good approximation of a thrusting spacecraft can be made in the laboratory.

## MECHANICAL DESIGN

A distinct design evolution was experienced in attempting to construct a test rig that would adequately simulate the conditions present during the burn of a solid propellant rocket motor. As a preliminary experiment it was primarily designed to provide a qualitative analysis of fuel and slag sloshing and aid in the development of future experimentation.

The design problem was to simulate rotation about the rocket's own axis and the subsequent precession about an associated axis, both of which are effects of spin stabilization. It was initially agreed that dual rotating shafts were best fitted to produce the kinematics of the situation, and subsequently the design problem was limited to developing a system that would drive the two shafts with correct direction and rates of spin. In order to achieve this effect several proposals were made, the first of which entailed using a set of belts and pulleys driven by a single electric motor. Succeeding designs included such elements as a planetary gear system, a set of rubber wheels, or a set of dual motors. In the end, the initial concept of belts and pulleys was adopted for their availability and ease of use.

The rig is mounted on a half-inch-thick aluminum table, approximately 1 m square and held up by four 9-in-long aluminum legs. The main shaft is positioned vertically through the middle of the table, housed by a bearing assembly mounted to the underface of the table. This shaft is driven by a belt, connected to a variable-rpm electric motor also mounted beneath the table. To the top of the main shaft is mounted a control arm made from an aluminum T beam. On one side of the control arm is the fuel tank assembly and on the other, an equal counterweight made of lead plates.

The hemispherical bowl, turned from a lucite block, is mounted to a second shaft that rotates within the bearing housing mounted to the control arm. Positioned on the main shaft and on the bottom of the second shaft are two pulleys. The pulley on the main shaft is secured and remains stationary with respect to the table. The other pulley is secured to the second shaft and produces the rotation of the bowl about its own axis. A crossing belt connects the two pulleys, and as the main shaft rotates at an average rate of 40 rpm, the second shaft rotates twice as fast in the opposite direction. In order to keep an adequate tension in the belt, the bearing assembly housing the shaft can shift horizontally by ±0.5 in. In addition, an idler is included on the control arm to guide the belt and maintain its tension.

During the next academic year (1990-1991) a sensor will be designed that determines the film thickness by measuring the capacitance between two platinum wires. This will hopefully provide a means to quantify the force and momentum produced by the rotating liquid in the bowl at various rpm. In order to incorporate this instrument, an electric connection to the bowl is needed through a set of slip rings in the rotating mechanism. Just below the bowl and above the bearing assembly is mounted the first slip ring, and at the bottom of the main shaft below the bearing assembly is mounted the second slip ring. To connect the wires from the control arm to the second ring, a hole is drilled down the center and through the entire length of the shaft. Through this hole the wires are run to the slip ring.

## COMPUTER SIMULATION

A theoretical analysis that approximates the fluid in the bowl with a point mass was developed. The result was a system of two ordinary differential equations that can be solved numerically by Heun's method for initial value problems. A code was generated that determines the x, y, and z coordinates of a "marble" rolling around inside the bowl given a friction factor, initial starting coordinates, bowl rpm, and nutation angle. The friction factor was varied to simulate the effects of fluid viscosity and friction of the point mass. The larger the friction value, the more of a damping effect the marble exhibited. For smaller values, the marble took longer to stabilize and rose higher in the bowl (see Fig. 4). When the actual experiments begin this fall, the code can be properly validated with better estimates of the friction factor, rpm, and nutation angles necessary to demonstrate a valid theoretical model and test rig.

## ACKNOWLEDGMENTS

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